An Analysis of Railroad Horn Detectability

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The U.S. Department of Transportation, Research and Special Programs Administration, Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility, in support of the Federal Railroad Administration (FRA), is conducting safety research to evaluate the effectiveness of various methods for reducing the number of accidents and resulting casualties at highway-railroad grade crossings. As part of this research, the effort reported here evaluates the probability of detection of railroad horn systems used as audible warning for motorists at highway-railroad grade crossings. To evaluate the detection probability, three sets of acoustic data were collected: (1) the acoustic characteristics of railroad horns, including sound level and directivity, (2) the insertion loss of motor vehicles, and (3) the baseline interior noise levels of motor vehicles. These data were used to determine the warning signal level to interior noise level ratio inside the motor vehicle, at the minimum distance which would give the motorist sufficient time to react and avoid a collision. Signal detection theory, which incorporates the motorist's prior expectations of encountering a train, is then applied to estimate the probability of detection of three currently used railroad horn systems at active and passive grade crossings.

1.0 INTRODUCTION

The Federal Railroad Administration (FRA) is conducting a comprehensive research program to develop methodologies for reducing the number of accidents and resulting casualties at highway-railroad grade crossings. In support of this effort, the Volpe Center's Acoustics Facility is conducting a study with the primary objective of optimizing the performance of railroad horn systems. The first part of this effort, summarized here, was to evaluate the probability of detection of railroad horn systems.

2.0 RAILROAD HORN SYSTEM CHARACTERISTICS

The acoustic characteristics, including sound level and directivity, of three different models of railroad horn systems were obtained through measurements, which are detailed in Reference 1. The three models were: A Leslie RSL-3L-RF and a Leslie RS-3L (both three-chime), and a Nathan K-5-LA (five-chime). The horn systems are representative of the horn systems currently being used throughout the United States.

Acoustic measurements were conducted with the horn systems mounted in their normal location atop a stationary locomotive. Acoustic data collected on a 30.5m circle around each horn system provided information on the directivity of the source, the maximum sound level produced, and the sound exposure level. Acoustic data collected 61 m to the front and to the side of the horn system provided information on the spectral output and drop-off rate. Figure 1 shows the one-third octave-band spectrum of the three systems at a position 61 m in front of the locomotive.

3.0 MOTOR VEHICLE CHARACTERISTICS

The acoustic characteristics of seven 1990/1991 model year motor vehicles were obtained through two sets of measurements, which are detailed in Reference 2. These vehicles were privately owned and provided by Volpe Center employees, and may not necessarily be representative of the national fleet.

3.1 Insertion Loss

The sound insulation characteristics (insertion loss) of seven motor vehicles were obtained by measuring the sound level broadcast by an artificial noise source at a reference position inside a stationary vehicle and at the same position with the vehicle removed. During testing, the vehicle was positioned so that the sound was incident upon the front, right, and left sides of the vehicle. It was found that the insertion loss did not vary significantly among the three incidence angles, thus a three-angle average insertion loss was calculated to represent each individual vehicle. The overall insertion loss of the motor vehicles tested was found to be approximately 25-35 dB(A). Figure 2 shows the three-angle average insertion loss as a function of frequency for the seven motor vehicles tested.

3.2 Interior Noise

Baseline interior noise levels of the same seven motor vehicles were measured while the motor vehicles traveled at a constant speed of 48.3 km/h, with windows closed, ventilation systems off, and stereo off. With this baseline level, only a minimal number of additional measurements would be required to account for the effects of open windows, ventilation systems, and stereo systems. These effects could be added on a case-by-case basis to represent many different types of operating conditions. For example, open windows will increase interior noise levels by 2 to 3 dB at low frequencies (<1000 Hz) and by 5 to 10 dB at high frequencies; air conditioning systems operating at medium or high will increase interior noise levels by 2 to 5 dB at low frequencies (<1000 Hz) and 5 to 10 dB at high frequencies; radio operation at a "normal volume" will increase interior noise levels by upwards of 10 dB. Overall interior noise levels were found to be approximately 55-65 dB(A). Figure 3 shown the interior noise levels as a function of frequency for the seven motor vehicles tested.

4.0 DETECTABILITY ANALYSIS

The three sets of measured data (horn system characteristics, vehicle insertion loss, and vehicle interior noise level) were then used in conjunction with acoustic theory and signal detection theory to develop a methodology to evaluate detection probability. For the purpose of this study, the probability of detection of a railroad horn system is defined as the probability that a person with normal hearing will hear the warning. Thus, the probability of detection can have values ranging from zero to one (0% to 100%). The probability of detection can be arrived at if the following two factors are known: (1) the difference between the signal level and the background noise level, defined as the signal-to-noise ratio (S/N); and (2) the perceived frequency of trains (i.e., the motorist's perception of the likelihood of an encounter with a train). The S/N was calculated using acoustic theory to propagate the warning signal into the motor vehicle at the minimum warning distance, defined as the minimum distance at which the motorist must detect the signal in order to avoid a collision (see Section 4.1.1). The perceived frequency of trains can be likened to a probability and can vary between zero and one. It is assumed that the higher the perceived frequency of trains, the more attentive the motorist will be in listening for the train horn. Using signal detection theory (this theory is further discussed in Reference 2), the probability of detection can be calculated for a range of perceived train probabilities and S/N, as shown in Figure 4. The required S/N ratio does not need to be present in each one-third octave-band; rather, to err on the side of safety, it was decided the required S/N must be present in a minimum of five one-third octave-bands.

Currently, there are two general types of grade crossing scenarios in which the train/motorist encounter might occur. In each scenario, the motorist has a different perception of the likelihood of encountering a train (perceived frequency). Based upon the perceived frequency, the probability of detection of each horn system was determined for a range of locomotive speeds (and therefore minimum warning distances) between 32.2 and 177 km/h. The two scenarios are as follows:

- Passive Crossings - The train/motorist encounter occurs at a passive crossing. In this scenario, the railroad horn is mounted on the locomotive, rail traffic volume is low, the road traffic volume is low, and the traffic speeds are relatively high. Through previous knowledge of the intersection, the motorist may perceive that there is only a small chance of encountering a train. Therefore, the perceived train frequency probability is set at 0.1.
- Active Crossings - The train/motorist encounter occurs at an active crossing. In this scenario, the railroad horn is mounted on the locomotive and the rail traffic volume and/or the road traffic volume is high. The motorist has presumably stopped at the lowered gates. Through previous knowledge of the intersection, and because the gates are lowered, the motorist may have a high expectation of encountering a train. Therefore, the perceived train frequency probability is set at 0.9.

4.1 Probability of Detection at Passive Crossings

As stated above, during the train/motorist encounter at the passive crossing, the motorist may perceive that there is only a small chance of encountering a train. At a typical passive crossing, most motorists have rarely encountered a train. Therefore, they may assume that, based upon prior experience, no trains will be approaching the crossing. Because there is no need to stop at the crossing unless a train is encountered, higher vehicle speeds may be encountered.

4.1.1 Minimum Warning Distance

Minimum warning distances for this scenario were calculated for various vehicle speeds and train speeds, using the methodology outlined by Aurelius and Korobow in Reference 3 and illustrated in Figure 5, summarized in the following paragraphs. It is defined as the distance between the motor vehicle and the front of the locomotive at the critical time (T_{cr}), as shown in Equation 1.

$$MWD = \sqrt{(T_{cr} * \text{Locomotive Speed(m/s)})^2 + (T_{cr} * \text{Vehicle Speed(m/s)})^2} \qquad (1)$$

T_{cr} is the instant at which detection must occur to avoid a collision; per Reference 3, it is a function of driver reaction time, the minimum motor vehicle stopping distance (MSD), critical track zone (CTZ), and motor vehicle length, as shown in Equation 2.

$$T_{cr} = \frac{\text{MSD(m)} + \text{CTZ} + \text{VehicleLength}}{\text{VehicleSpeed(m/s)}} + \text{DriverReactionTime} \qquad (2)$$

These calculations assumed a CTZ of 9.14 m, encompassing the railroad tracks, a vehicle length of 5.8 m, and a driver reaction time (i.e., the time elapsed between the instant when the warning signal is heard and when the brake is engaged) of two and one-half seconds, in accordance with Reference 5. Also inherent in the calculation is perpendicularity of the railroad track and roadway. Minimum safe motor vehicle stopping distances (MSD) were calculated as follows, using guidelines in the 1982 *Transportation and Traffic Engineering Handbook (4)*:

$$\text{MSD(m)} = V_m^2 / 255(f \pm g), \qquad (3)$$

where V_m is the motor vehicle speed (km/h), g is the pavement grade, and f is the skidding friction coefficient (0.36 at 48.3 km/hr), in accordance with the American Association of State Highway and Transportation Officials (AASHTO). For the purpose of this study, calculations assumed no grade.

4.1.2 Signal Detection

In order for the motorist to take the appropriate action in time to avoid a collision, the warning signal must be detected at or before the instant of reaching the minimum warning distance. As stated earlier, the warning signal probability of detection is calculated for a range of locomotive speeds based on the five highest one-third octave band S/N ratios at the minimum warning distance.

To determine the probability of detection, the warning signal level inside the vehicle at the minimum warning distance was compared with the average measured background noise level for a vehicle traveling 48.3 km/h. This speed is chosen for this analysis because it was the speed at which interior noise measurements were collected. If the vehicle is traveling faster, which is likely at this type of crossing, the interior noise may be greater; if the vehicle is traveling slower, the interior noise may be less. Signal levels *inside* the vehicle were calculated by subtracting the average measured motor vehicle insertion loss in each one-third octave band (Figure 2) from the warning signal levels obtained through measurements, extrapolated to various distances using a conservative drop-off rate of 7.5 dB per distance doubling, in accordance with empirical rules-of-thumb employed by the Federal Highway Administration for propagation over grass-covered terrain *(6)*. Following is an example calculation:

A motorist is approaching a passive grade crossing (perceived train frequency probability = 0.1) at 48.3 km/h. A locomotive is approaching the grade crossing at 80.5 km/h. The locomotive is equipped with a Leslie RSL-3L-RF. Using the equations in Secion 4.4.1, minimum required warning distance for this example is calculated to be 143.7 m.

1.) From Reference 1, the signal level at 61.0 m for the Leslie RSL-3L-RF is as follows:

Freq (Hz)	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
	61.04	60.83	80.39	85.09	81.75	84.72	87.62	88.80	84.65	81.78	79.62	79.89	76.22	71.61	67.41	63.18	59.12	55.24	51.47

2.) The signal level at 143.7 m is calculated using a drop-off rate of 7.5 dB per distance doubling (25log(61/143.7)).

Freq (Hz)	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
	51.74	51.53	71.09	75.79	72.45	75.42	78.32	79.5	75.35	72.48	70.32	70.59	66.92	62.31	58.11	53.88	49.82	45.94	42.17

3.) The signal level inside the car at 143.7 m is calculated by subtracting the average insertion loss (Figure 2) from the above level.

Freq (Hz)	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
	39.58	36.94	56.83	60.44	51.96	51.07	50.14	50.21	46.88	42.61	36.49	38.53	33.19	28.31	24.06	19.01	11.54	3.36	-1.62

4.) The average interior noise level is obtained from Figure 3.

Freq (Hz)	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
	60.69	59.15	57.60	56.41	53.17	50.67	46.81	44.81	43.92	41.97	39.82	36.42	33.76	31.34	29.82	26.40	24.13	22.49	21.60

5.) The S/N is obtained by subtracting 4.) from 3.).

Freq (Hz)	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
	-21.10	-22.20	-0.76	4.03	-1.21	0,40	3.33	5.39	2.96	0.65	-3.34	2.11	-0.57	-3.03	-5.76	-7.39	-12.59	-19.12	-23.22

6.) The five highest S/N ratios are highlighted. The minimum of these is 2.11 dB. From the Figure 4, the detection probability for a S/N ratio of 2.11 dB and an expected train probability of 0.1 is ~0%.

The ranges of detection probabilities for the motorist approaching a passive crossing at a speed of 48.3 km/h are as follows:

- >99% at a locomotive speed of 32.2 km/h to 99% at a locomotive speed of 177 km/h for the Nathan K-5-LA.
- 75% at a locomotive speed of 32.2 km/h to ≈0% at locomotive speeds greater than 96.6 km/h for the Leslie RSL-3L-RF.
- 10% at a locomotive speed of 32.2 km/h to ≈0% at locomotive speeds greater than 48.3 km/h for the Leslie RS-3L.

4.2 Probability of Detection at Active Crossings

The active crossing represents a situation where the motorist has stopped before the lowered gate, and is waiting to detect the horn as confirmation of the approaching train. In this scenario, the motorist has a high expectation of encountering a train.

4.2.1 Required Warning Distance

The required warning distance in this scenario is again defined as the distance between the motor vehicle and the front of the locomotive at the critical time (T_{cr}). Because it is assumed that the motorist has slowed down or is stopped at the lowered gate, T_{cr} is now only a function of train speed, driver reaction time, and the time it takes the motorist to traverse the gate.

An estimate of T_{cr} is based on the following scenario: The motorist has stopped at a crossing with lowered gates. If the horn is not detected, the motorist will need approximately 2.5 seconds to make the decision whether or not to continue around the gates. If the motorist makes the unsafe and illegal decision to continue around the gates and across the tracks, they will need approximately 7.5 seconds to do so. Thus, T_{cr} is assumed to be 10 seconds before the locomotive arrives at the crossing.

4.2.2 Signal Detection

To determine the probability of detection, the warning signal level inside the vehicle at the minimum warning distance is compared with the average measured interior noise level for a vehicle traveling 48.3 km/h (Figure 2). Although the minimum warning distance is based upon the assumption that the vehicle is stopped at the gates, one-third octave-band interior noise levels at 48.3 km/h are used due to a lack of one-third octave-band interior noise data at idle. Overall interior noise levels published by several automotive magazines show that the interior noise levels may be on the order of 15 to 25 dB(A) lower at idle than at 48.3 km/h, therefore, this assumption is conservative and errs on the side of safety.

The ranges of detection probabilities for a motorist stopped at an active crossing are as follows:

- >99% at a locomotive speed of 32.2 km/h to 98% at a locomotive speed of 177 km/h for the Nathan K-5-LA.
- 98% at a locomotive speed of 32.2 km/h to ≈0% at locomotive speeds greater than 144.8 km.h for the Leslie RSL-3L-RF.
- 96% at a locomotive speed of 32.2 km/h to ≈0% at locomotive speeds greater than 96.6 km/h for the Leslie RS-3L.

5.0 CONCLUSIONS

This paper summarizes evaluation of the probability of detection of railroad horn systems used as audible warning for motorists at highway-railroad grade crossings. The evaluation could be further enhanced by: (1) incorporation of recent advances in the application of signal detection theory*(7),* and (2) incorporation of automotive interior noise data from late-model vehicles at a range of speeds from 0 to 96.6 km/h.

6.0 REFERENCES

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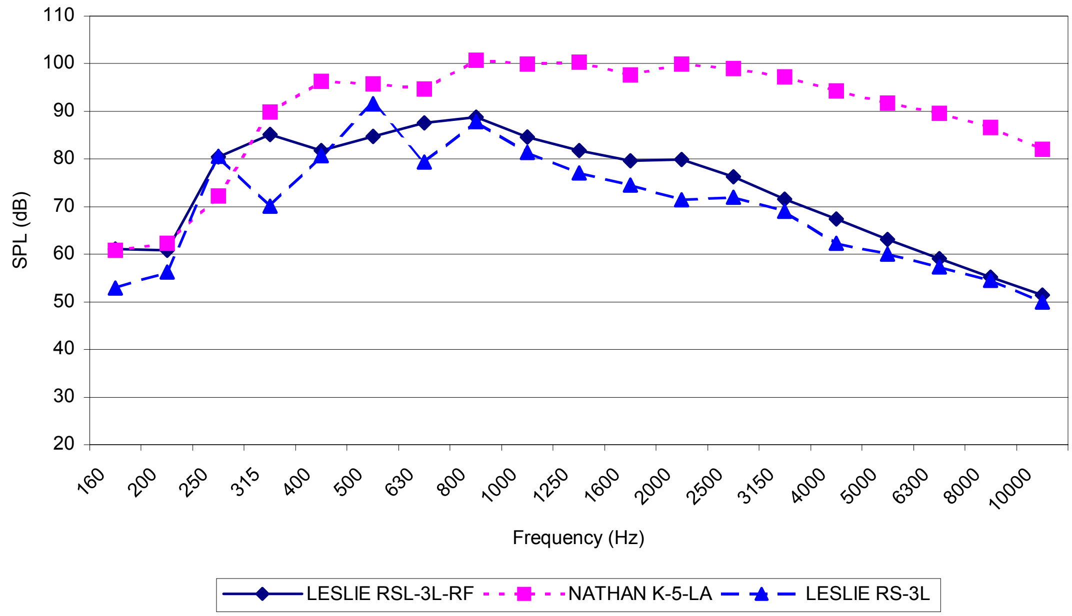

Figure 1. Spectral Characteristics of Three Railroad Horn Systems

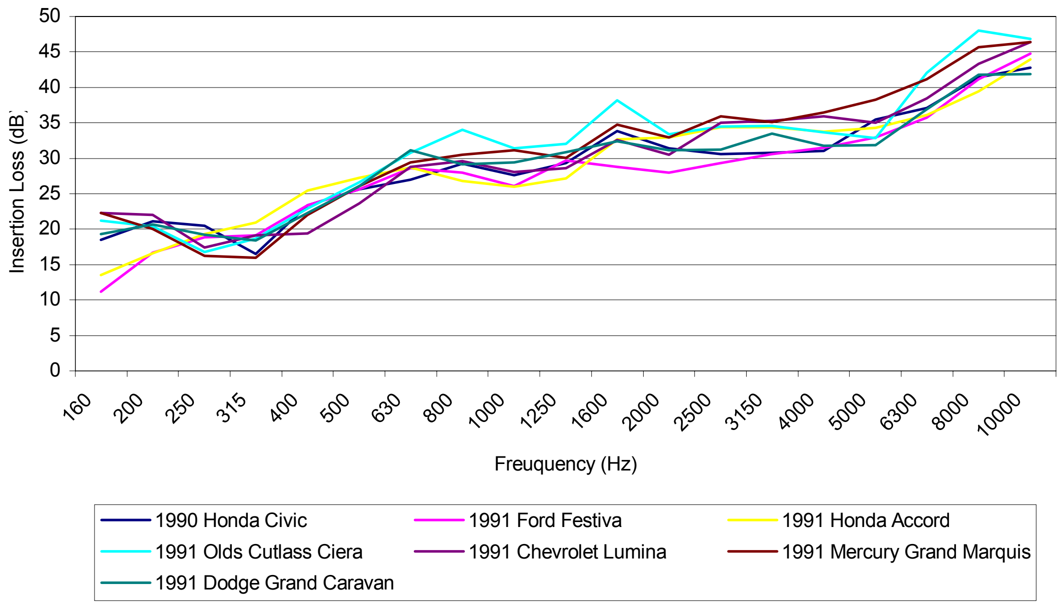

Figure 2. Insertion Loss Characteristics of Seven Motor Vehicles

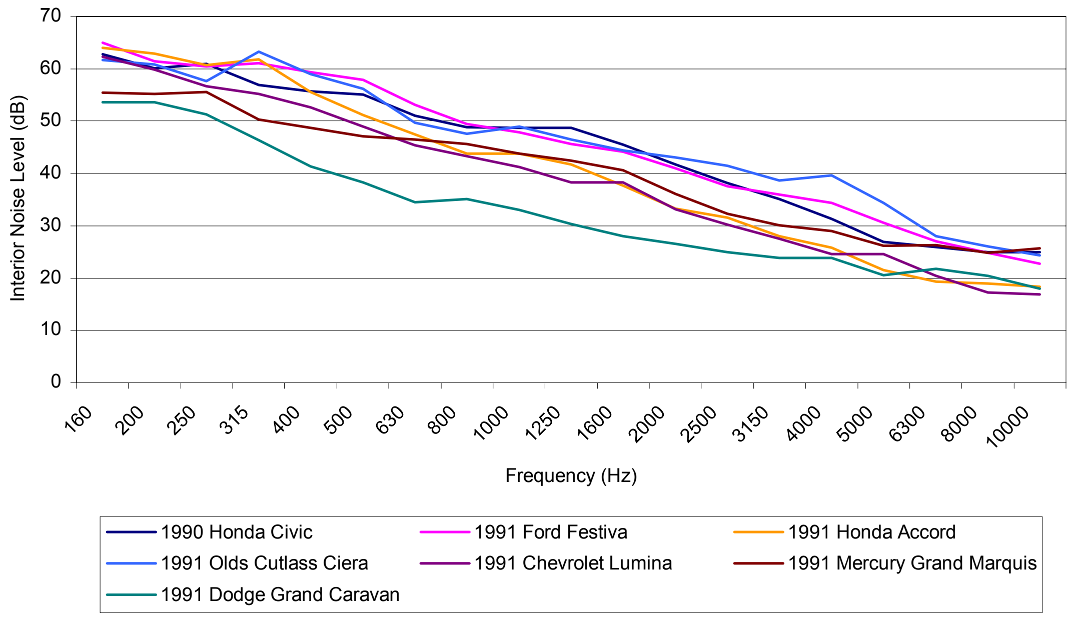

Figure 3. Baseline Interior Noise Characteristics of Seven Motor Vehicles

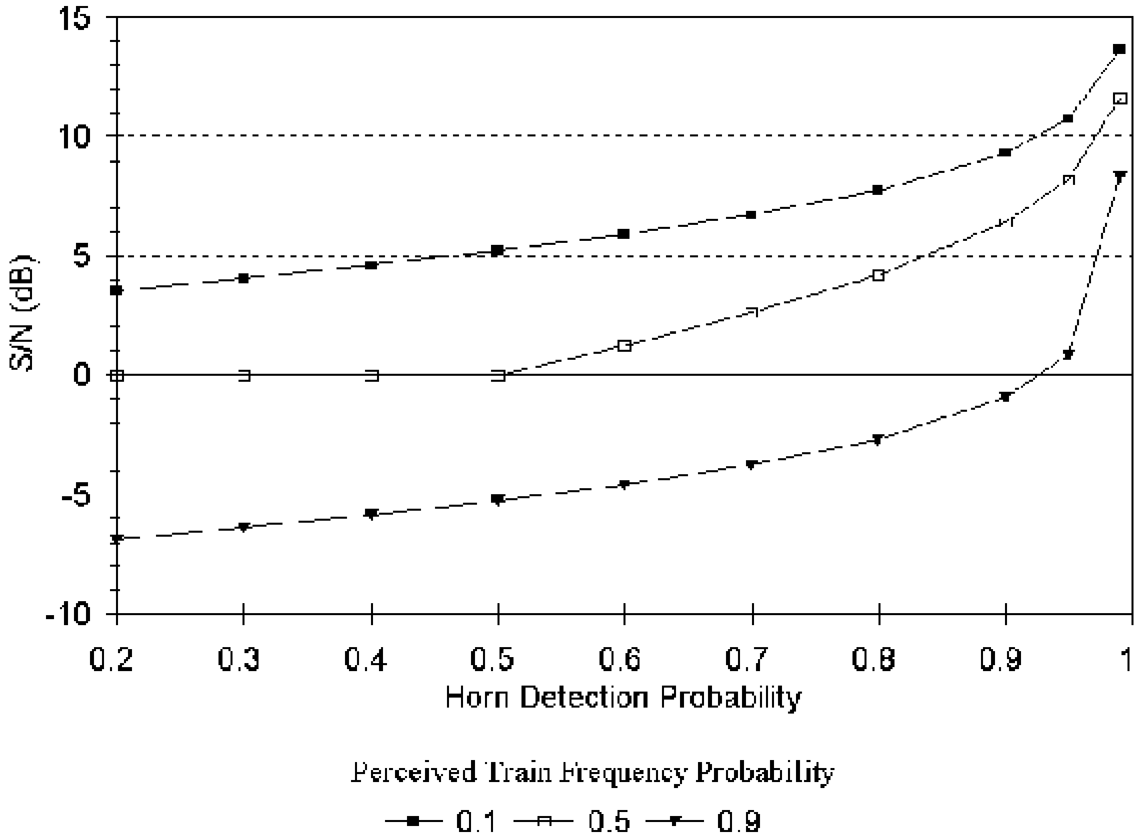

Figure 4. Horn Detection Probability vs. S/N

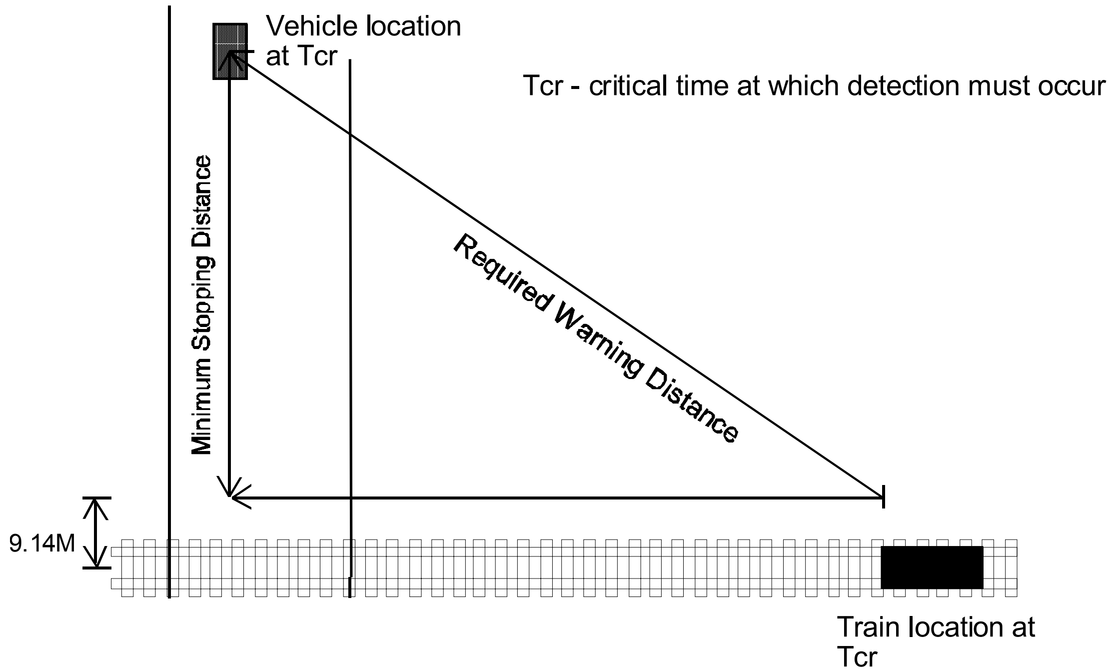

Figure 5. Minimum Warning Distance